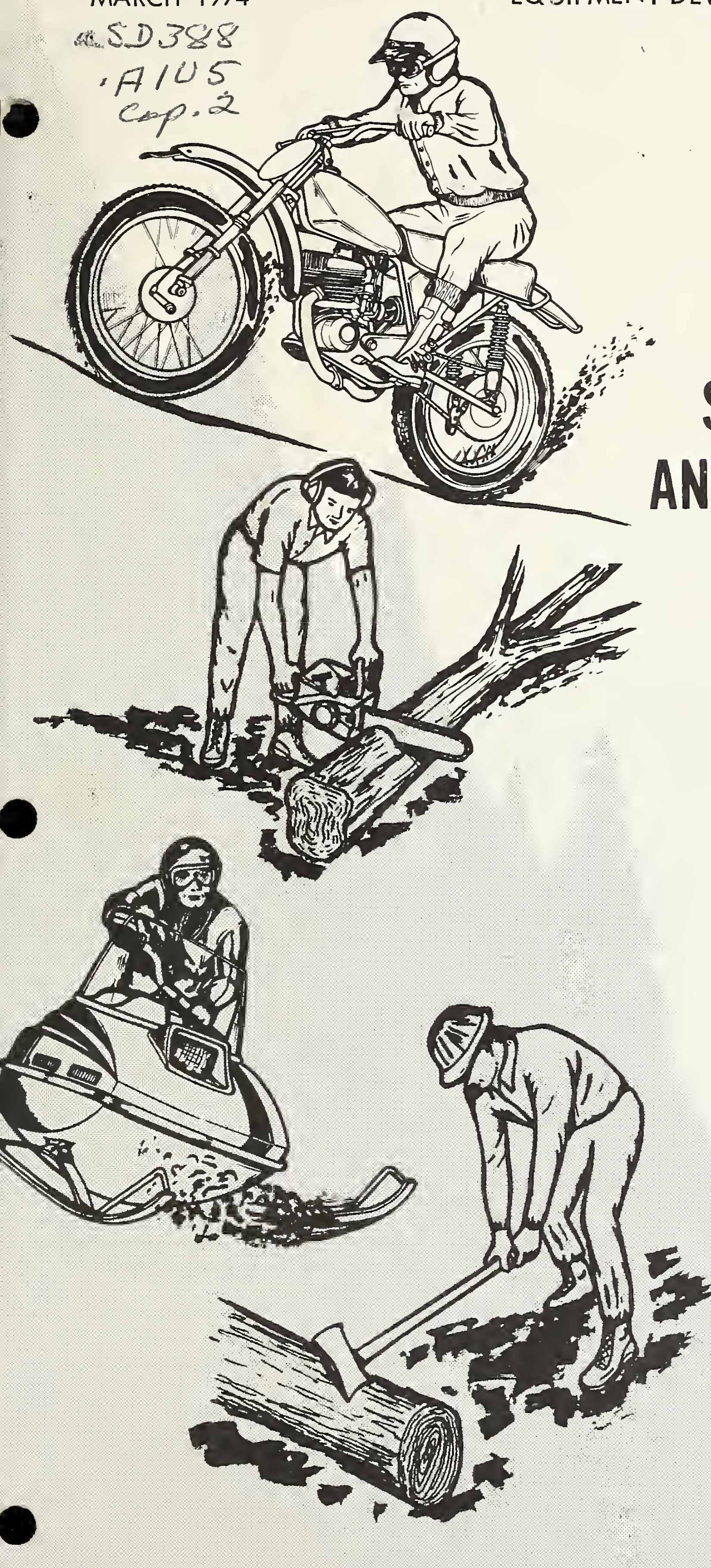
MARCH 1974 EQUIPMENT DEVELOPMENT AND TEST REPORT 7120-6



SOUND PROPAGATION AND ANNOYANCE UNDER FOREST CONDITIONS

U. S. Department of Agriculture, Forest Service San Dimas Equipment Development Center

Equipment Development and Test Report 7120-6

SOUND PROPAGATION AND ANNOYANCE UNDER FOREST CONDITIONS

by

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ABSTRACT

A discussion of how sound is attenuated under forest conditions is presented as background information to this study of sound propagation and annoyance in the forest environment. The Equipment Development Center at San Dimas performed tests to determine the effect of forest conditions on the propagation of sound and conducted an investigation of the annoyance caused by noise from common forestry operations. The effect of naturally occuring forest vegetation on the propagation of sound was experimentally determined to be negligible, when compared to the effect of other parameters, such as distance and atmospheric attenuation. Acoustic annoyance under forest conditions was discovered to be more a function of the mere detection of a given acoustic signal and its "unnaturalness," than its level or intensity.

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INTRODUCTION

Many factors affect the out-of-doors transmission of sound. Those related to distance and atmospheric conditions, such as wind and temperature, have been thoroughly investigated and documented (2, 3, 8, 15, 23). However, not nearly so much study has been given to the effect of trees, grasses, and shrubs on the outdoor propagation of sound. The first systematic work was apparently done by Eyering in the Panamanian jungle back in 1946 (11). Several authors (9, 27) have reported experimental results in dense evergreen forests, and some searching theoretical and experimental work was done in Canada by Embleton and his colleagues (10, 21). The Forest Service co-sponsored a study of trees and shrubs, planted in rows, as noise screens (9).

Some authors have made sweeping statements that trees absorb sound at the rate of 6 to 8 dB per 100 ft (19). Under selected conditions and careful planting, these results could probably be achieved. However, there is considerable variability reported in the literature on the amount of attenuation caused by trees. The Equipment Development Center, therefore, undertook to measure the propagation of sound under typical forest conditions.

Measurements of the propagation of sound created by several common forestry activities were made. The effect of distance and atmospheric parameters on these sounds were then calculated. From these considerations, the excess attenuation caused by the forest itself was calculated. This included the effect of all vegetative cover, since it is difficult—if not impossible—to separate the effect of grasses and low ground cover from that of trees and brush.

Another objective of the project was to quantify noise annoyance under forest conditions. A great deal of work has been done to quantify acoustic annoyance (5, 6, 12, 17, 18). Spieth has attempted to define a threshold of annoyance for work situations (25). However, the measurement of annoyance, especially under such specialized conditions as in the forest, is an extremely subjective proposition (15). Measurements of the annoyance of various common forestry noises, the same ones used in the evaluation of excess attenuation, were made using a popular scale, the A-weighted sound pressure level (dBA).

SOUND PRIMER

Let's review a few definitions and basic assumptions.

Sound is defined as "an oscillation in pressure . . . (of) a medium (air) or the superposition of such propagated oscillations . . ." (1). Sound, then, is a physical phenomenon, and in answer to the old question, "If a tree falls in the forest and no one is there to hear it, does it make any sound?," the answer must be "yes."

Noise (annoyance) on the other hand is defined as "any undesired auditory sensation" (1). Noise must be perceived to be noise. Therefore the answer to the old question, "If a tree falls in the forest and no one is there to hear it, does it make any noise?," must be "no."

The sounds studied all took place out-of-doors. Figure 1 represents schematically the three components of any sound transmission system: the source (in this case a chain saw, trail crew, etc.); the path (the atmosphere modified by the presence of trees, shrubs, grass, etc.); and the receiver (in this case the data recording instrumentation). This source-path-receiver concept is known as the systems approach and was pioneered by Dr. Beranek of MIT (2).

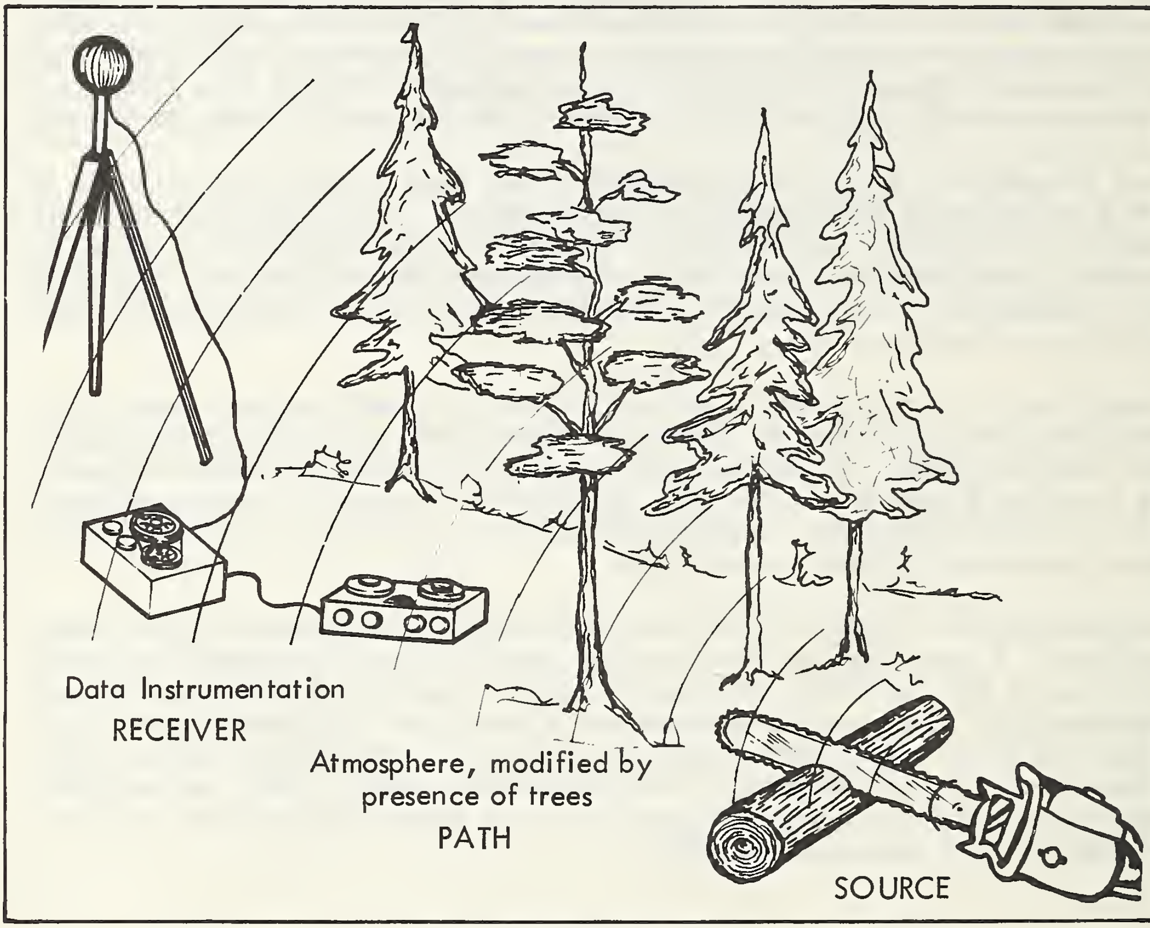


Figure 1. A complete sound system: source, path, receiver.

A unit that needs to be defined is the decibel (dB). This is a logarithmic measure of sound pressure, defined by the formula:

$$\text{Level, dB} = \log_{10} \frac{P_1^2}{P_o^2}$$

where P_o = reference pressure, 0.0002 dyne/cm^2

P_1 = measured sound pressure, dyne/cm^2

Being a logarithmic quantity, dB's are not directly additive; e.g., 70 dB + 70 dB = 73 dB, approximately (not 140 dB).

The frequency of sound is translatable in human terms to its pitch, and represents the number of oscillations per second. A sound can, of course, contain more than one frequency. All of the sounds under present discussion do. An octave represents a band of frequency whose highest component is double that of the lowest frequency component. An octave band sound pressure level in dB, then, is the sound pressure level of that portion of the total sound which lies between, say, 707 and 1,414 Hertz (Hz, cycles per second). So a 1/3 octave band sound pressure level would be the sound pressure level of that portion of the total sound which lies between, for example, 707 and 891 Hz, or 891 and 1,122 Hz, or 1,122 and 1,414 Hz.

The term sound pressure level needs some clarification. "Sound pressure level" implies that the total energy of the sound is being considered. In figure 2 the curve marked "C" (also referred to as "all pass") is the frequency response of an instrument that measures sound pressure level; no frequencies in the acoustic range are emphasized or deemphasized. This curve is essentially linear. The slight roll-off in the curve at each end of the spectrum indicates the best frequency response that can be achieved by reasonably priced ($500-1,000) sound-level meters. In other words, sound pressure level implies no frequency emphasis or deemphasis. The total energy of the sound is being measured or talked about.

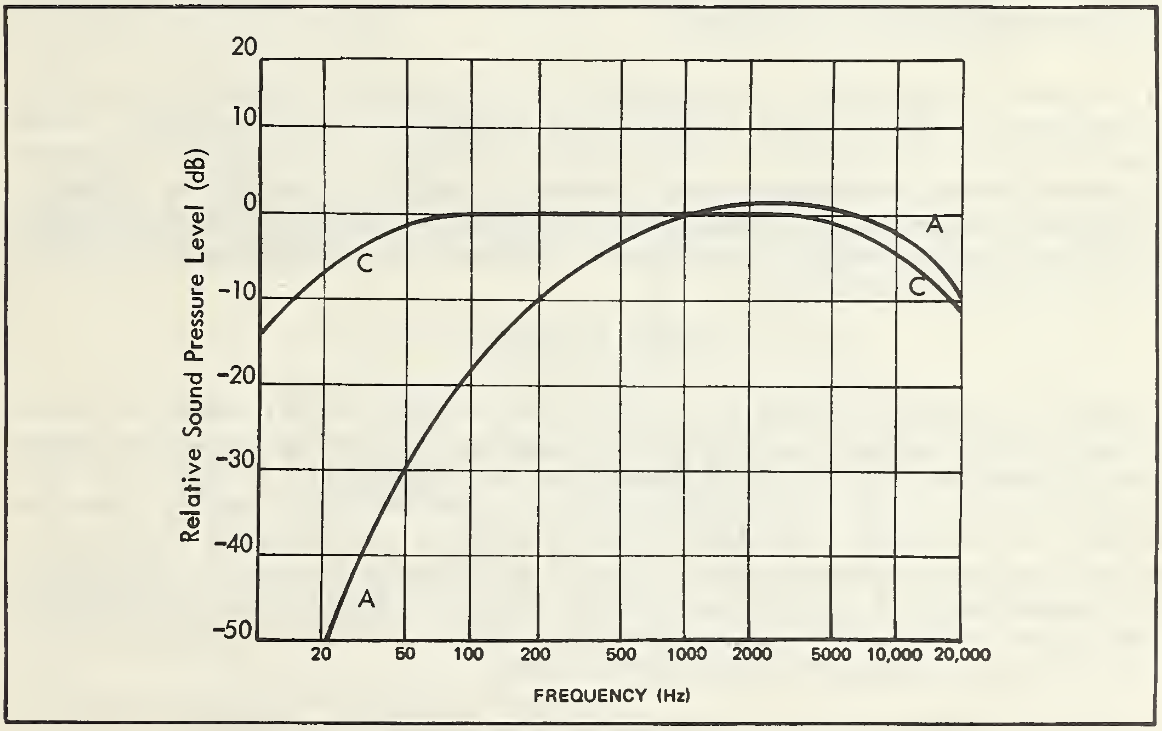


Figure 2. Weighting for C and A scales.

Now look at the curve marked "A". This indicates a considerable deemphasis of lower frequencies and a slight emphasis of frequencies between 1,000 and 5,000 Hz.

This is the so-called A-weighting curve, and when sound level is talked about it is understood that the sound has been weighted according to the values shown in this curve. The A-weighting curve is designed to simulate the human hearing mechanism's frequency response. The ear/brain combination deemphasizes the low frequencies and slightly emphasizes the frequencies between 1,000 and 5,000 Hz. Thus, when sound levels are discussed it is implied that they have been weighted by this A curve. To avoid confusion, sound pressure levels will be referred to as dBC and sound levels in units of dBA.

Numerous schemes have been devised that attempt to relate a measurable sound pressure quantity to human response under various conditions. Some of these will be dealt with further under the section "Investigation of Annoyance." However, the two scales mentioned are by far the most popular, and are applicable to the work discussed in this report.

SOUND ATTENUATION IN THE FOREST

A question which is often asked of acoustical engineers is, "How far away from noise source X do I have to remove receiver Y before receiver Y no longer hears noise source X?" To answer this question, the acoustical engineer inevitably needs a great deal more information than that initially available from those seeking the answer. Indeed, the answer is not calculable in any exact sense, and involves factors not considered in this report.

If the question were asked, "In the forest, how far away from noise source X, which is producing 75 dBA at 50 ft, must receiver Y be to receive only 60 dBA?," then the answer can be calculated. This section of the report deals with the parameters needed to answer this second question—distance, atmospheric conditions, and forest conditions. The effects of distance and atmospheric conditions are well documented, and were not experimentally investigated. However, the effect of forest conditions was extensively investigated.

Effect of Distance

Doubling the distance between a sound source and receiver will reduce the sound pressure at the receiver by a factor of 4. Therefore, the sound pressure level measured at distance X will be 6 dB lower than that measured at distance $\frac{1}{2}$X. This phenomenon is called <u>spherical divergence</u>. In the "far field," that is, when the receiver is far enough away from the sound source so that the source is acting like a point source (a distance of about four times the major dimension of the source), this approximation is remarkably accurate. If we are fairly close to the sound source, but in the far field, a small change in distance will result in a considerable reduction in sound pressure level at the receiver.

Mathematical manipulation of the equation given above as the definition of decibel leads us to the following equation:

$$L_x = L_o - 20 \log_{10} \frac{D_x}{D_o}$$

where L_x = the level to be calculated at a desired distance

L_o = the level at a given distance

D_x = the distance from the source for which L_x is to be calculated

D_o = the given distance at which L_o is measured

(L is level in dB; D is distance in consistent units)

This equation predicts the decrease caused by spherical divergence. If you pick any number for L_O and D_O, say 75 dB and 50 ft, and substitute for D_X twice D_O, that is 100 ft, you will see that $L_X = 75 - 6$ or 69 dB. Another distance doubling (200 ft), and the level becomes 63 dB.

Atmospheric Conditions

In addition to the effect of distance, and the effect of path modifiers such as trees (which was to be investigated), atmospheric conditions play an important role. The atmospheric conditions that need to be considered are:

- Attenuation caused by absorption in air
- Attenuation caused by fog, rain, or snow
- Attenuation caused by wind and temperature gradients, atmospheric turbulence, and ground effects.

In discussing these three parameters it is assumed that the sound source is not so intense that the air is "overdriven." Therefore, non-linear effects (air distortion) are not considered.

Attenuation Caused by Absorption in the Air

A soundwave traveling through still, homogenous air loses energy through the effects of heat conduction and radiation, viscosity, and diffusion in the air. The exact nature of the mechanism of this loss is quite complex and, in practical situations, calculations are difficult to make. Both the humidity of the air and the frequency

of the sound markedly affect absorption, as is seen in table 1. Note that for frequencies up to 1,000 Hz an absorption of 2 dB per mile is given for all conditions encountered (21).

Table 1. Sound pressure level decreases caused by energy absorption in atmosphere.

Relative humidity (%)	Temperature (°F)	1,000 Hz and below	2,000 Hz	4,000 Hz	6,300 Hz
		(dB per mile)			
30	59	2	25	85	185
	68	2	21	66	147
	77	2	20	54	120
	86	2	19	49	99
50	50	2	17	50	110
	68	2	17	42	88
	77	2	17	41	77
	86	2	16	41	75
70	50	2	15	39	79
	68	2	15	37	70
	77	2	15	37	68
	86	2	14	36	67

Attenuation Caused by Fog, Rain, or Snow

On days of fog, drizzle or light, falling snow, sound is normally observed to carry further outdoors than on a clear day. This is not attributable to any remarkable acoustic property of precipitation, but to the fact that temperature and wind gradients tend to be small under these conditions. Although some systematic investigations of the effect of fog on atmospheric absorption have been made (16) they do not seem to be conclusive, and it is logical to assume that the effects of precipitation are negligible (2).

Attenuation Caused by Wind and Temperature Gradients, Atmospheric Turbulence, and Ground Effects

Over open, level ground, appreciable vertical temperature and wind gradients almost always exist; thus the refraction of sound waves is a probability. This refraction can lead to "shadow zones" into which no direct sound can penetrate (2). However, temperature and wind gradients are not usually present in areas covered with trees (2). Because of this, and because all measurements in the present study were made in conditions of near zero wind, the effects of wind and temperature gradients were not considered.

TESTING THE EFFECT OF THE FOREST

Since the effects of distance and atmospheric conditions on the attenuation of outdoor sound could be calculated, it remained to determine under actual field conditions what effect, if any, typical forest settings would have on the propagation of sound. What we were seeking was the magnitude of any sound pressure level that might occur over and above that predicted by distance and atmospheric conditions calculations; i.e., the excess attenuation due to conditions unique to the forest.

A complete description of the test method and instrumentation used can be found in appendix I. Briefly, the approach involved the selection of 6 typical forest settings and 11 sound sources that usually emit noise within forest boundaries. The sound pressure level of these sources was measured at various distances at each of the selected forest sites having a typical dominant vegetation-topography.

Test Sites

Six different settings were found within the California Region of the Forest Service to represent the typical forest environment. The experiments were conducted at the sites described in the paragraphs that follow.

Mature Coniferous Forest

This area, located in the Sequoia National Forest, is shown in figure 3. The elevation was approximately 6,000 ft on the Kern Plateau. Ground cover was sparse, consisting of low brush and pine duff. A small amount of snow was on the ground, but none remained on the trees. The test area was relatively flat. Visibility along the line of sight was about 300 ft.

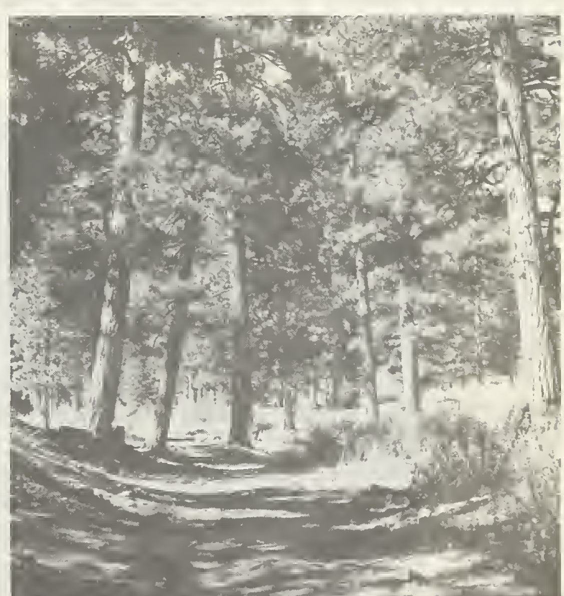


Figure 3. Site 1, Kern Plateau.

Across Water

This location was at Jameson Lake on the Los Padres National Forest, figure 4. It was surrounded by semi-arid, rugged mountains, but was large enough that the surroundings did not affect the sound field.

Figure 4. Site 2, Jameson Lake.

Broadleaf Area

This site, located in the Los Padres National Forest, consisted mainly of live oak, with a ground cover of short grass and oak duff. The test area was fairly flat (see figure 5).

Figure 5. Site 3, Broadleaf area.

Burned-over Brush

This site was in the Los Padres National Forest. The terrain was steep (20 to 70 percent grade) and rocky. Grass about 8-in. tall covered the ground, and a few bushes had begun to grow. Data from this site were inconsistent, so they were not used.

Heavy Brush

This site (see figure 6) was near the Dripping Springs Station on the Cleveland National Forest. The brush was about 7-ft tall and quite dense. The terrain was steep and rugged, visibility was less than 50 ft.

Figure 6. Site 5, heavy brush.

Open Meadow

Figure 7 shows the meadow used, near the Pendola Guard Station on the Los Padres National Forest. The dead annual grass was between 10 and 18 in. tall. The test

Figure 7. Site 6, meadow.

area was flat, and the trees and surrounding hills were far enough away so as not to affect the sound field.

Sound Sources

The following sound sources were used for data; the figures in parenthesis following each source are the approximate C-weighted dB levels at 100 ft.

1. Sawing logs with two-man saw (55 dBC).
2. Chopping with an ax (75 dBC).
3. Using a pick, a shovel, and a combination thereof (76 dBC).
4. Rock drill and sledge (75 dBC).
5. Discharging firearms (two were used, a .22 caliber pistol and a 30-06 rifle) (107 and 130 dBC).
6. Man shouting as loudly as possible (67 dBC).
7. Two trail crews working with hand tools (inconclusive [1/]).
8. Dodge pickup truck, 1966 V8 (73 dBC).
9. Motorcycle, 350-cc "Velocette" (80 dBC).
10. Small, high-speed, 2-stroke engine, McCulloch portable welder (95 dBC).
11. Chain saw, Wright model 30 (93 dBC).

Four of the above sound sources (ax chopping, pick/shovel work, the rock drill/sledge, and the firearms) may seem to have unusually high dBC levels. This is because these levels were measured with an impact analyzer, which has a considerably faster response than the human ear. The first seven items in the sound source list are generally considered acceptable by the Forest Service, even under criteria for wilderness conditions. The last four on the list, vehicles and power tools, are considered intruders in wilderness areas.

Appendix II shows 1/3 octave spectra for a few representative sounds. These spectra were taken out-of-doors at 100 ft from the source.

At first we considered using a "white noise" sound source rather than attempting to simulate actual forestry operations. (A <u>white noise</u> is a noise that contains equal levels of all frequency components in the entire acoustic range.) This idea was rejected for two reasons. The first was the difficulty in obtaining a true white noise in the field. The second was that we had no knowledge of what the actual spectra of representative forestry operations looked like. Therefore, even if we did arrive

[1/] Not a "point" source since crew members spread out over area to be worked.

at attenuation figures for white noise, we would still have little feel for how forest conditions affected the noise of actual operations.

TEST RESULTS

At Six Different Sites

Table 2 presents the excess attenuation data determined at each site and compares these with values found in the literature. Shown with each measured value is the probable error, of the mean, for that value.

Table 2. Excess attenuation due to forest conditions.

Site No.	Description	Terrain loss, dBC/100 ft Measured value	Reported in literature
1	Mature conifers, visibility 300 ft	-0.5 ±0.4	1 to 5 (11) 2 (27)
2	Across water	-1.3 ±0.1	0 (2)
3	Mature oaks	-1.3 ±0.4	-
4	Burned-over brush	Inconclusive	-
5	Dense brush, 7-ft tall, visibility less than 50 ft	0.8 ±0.3	1 (11)
6	Open meadow, 10-18 in. grass	1.0 ±0.2	0.3 (11)

Site 1

The results of this study show a small negative excess attenuation coefficient. This negative coefficient would seem to mean that sound attenuates slightly less than would be expected by divergence alone, a conclusion not in agreement with the work done by other researchers. The probable reasons for this variation are the open nature of the test site selected and the bareness of the tree trunks to a considerable height. This bareness in effect creates an open area. Because of tree spacing, there are relatively few trunks between the source and receiver. The tree canopies probably prevent much vertical wind or temperature gradient.

Work done by Cook and Van Haverbeke (9) seems to support the hypothesis that the open area underneath the tree canopies does not provide much excess attenuation. They measured the excess attenuation of one area in a section of rather scrawny trees, where the passage of light was relatively unobstructed. They also measured, in the same area, a section in which the trees were more healthy and the foliage was denser. A marked increase in excess attenuation was seen for the healthy trees.

Cook states that a major difficulty in attempting to relate forest density to noise reduction is that no completely satisfactory method has yet been devised for numerically measuring density. Although visibility distance would seem to be a valid approximation of forest density, not enough work has been done to verify this relationship (9). 2/

Site 2

Spherical divergence and atmospheric losses could be expected to provide attenuation of sound across still water. It is possible that some reflection of sound could take place from the surface of still water. One would, therefore, expect a zero or small negative excess attenuation coefficient. The experiment confirmed this expectation.

Site 3

The measured excess attenuation coefficient at this site was negative. This finding is somewhat surprising. One possible explanation is the physical arrangement of the site. The trees are largely bare up to a height of 15 ft or so. It is possible that some of the sound energy that normally would have escaped was reflected back toward the receiver.

The explanation given under site 1 above is probably also valid for this area.

Site 5

The measured excess attenuation coefficient in dense, 7-ft tall brush is in good agreement with that given by Eyering for thick, 6-ft tall grass and brush.

Site 6

The excess attenuation coefficient measured for the open meadow was somewhat greater than that given by Eyering. Since wind and temperature gradients are very important in the attenuation of sound over open ground, estimates of these parameters had to be made. If more accurate measurements of these conditions had been obtained, perhaps closer agreement would have been reached.

The total excess attenuation that could be expected at sites 5 and 6 would probably not be even as much as that expected in forests, because of the ease with which noise would propagate over the vegetation at these sites.

Discussion

Table 3 shows the results of three studies of excess attenuation reported in the literature. The excess attenuation coefficient is a function of frequency in all cases, so the coefficient shown in the table is calculated for a noise source whose energy is concentrated between 300 and 600 Hz. This range approximates the case for most of the noises investigated in our study.

2/ Cook, David I., 1968, Personal Conversation, Univ. of Nebraska, Lincoln, Nebr.

Table 3. Summary of literature values for forest excess attenuation loss.

Reference	Condition	Excess attenuation dB/100 ft
Eyering (11)	Panamanian jungles, leafy, visibility about 200 ft	$1\frac{1}{2}$
	Panamanian jungles, very dense, visibility about 50 ft	3
Weiner & Keast (27)	Dense Maine evergreen woods, visibility 70–100 ft, tree height 20–40 ft	2
Embleton (10)	Four species: cedar, spruce, pine deciduous; visibility from 15–60 ft for conifers, up to 150 ft for deciduous	8

Embleton's work shows that excess attenuation is independent of the species. On the other hand, Eyering states that for frequencies above 500 cps, the coefficient of excess attenuation is very sensitive to type of vegetation.

The maximum excess attenuation caused by the forest is about 10 dB for frequencies lower than 1,000 Hz, and 15 dB for frequencies above 1,000 Hz (21). These figures are not greater because noise is propagated up through the canopy of the tree over the top and down to the receiver. For most forest types, the density of the canopy does not seem to have a great effect on this figure (2, 21). In some cases, considerable discrepancy exists between our results and those given in table 3. There are several possible explanations for this. The tests of Eyering, Weiner and Keast, and Embleton were conducted under conditions significantly different from those of our test. But the most readily acceptable reason is that given in the site 1 results—that the bare trunks of the trees do not serve to attenuate sound. The negative excess attenuation coefficient figures shown in table 2 are certainly not to be interpreted literally. If strictly applied, they would indicate that at some great distance the sound pressure level of a source would be increased back to the level at the source. Using the value obtained for site 3, −1.3 dB per 100 ft, this distance would be about $\frac{1}{2}$ mile, which is patently ludicrous. What the figures do indicate is that the attenuation caused by the forest is small and probably negligible for most of the conditions encountered during this study.

This is not to imply that trees cannot be effective as sound barriers. Indeed, thorough work has shown that they can be used to great advantage (9). What it does mean is that naturally occurring ground cover and trees, with the possible exception of heavy brush, should not be counted upon to provide much attenuation over that predicted by atmospheric absorption and spherical divergence.

For the assumption of spherical divergence to be valid, reflections and directivity index must both be zero. These conditions could not have been met in those situa-

tions where negative terrain loss was found. From table 2 we see, then, that there must have been some reflection at sites 1, 2, and 3, whereas at sites 5 and 6 the spherical divergence, i.e., free field, conditions may well have been met.

Myles, et al., (21) suggest the use of 2 dB per 100 ft as an excess attenuation coefficient for the forests typical to eastern Canada, with maximum excess attenuations of 10 dB at low frequencies and 15 dB at high frequencies.

INVESTIGATION OF ANNOYANCE

At the start of the sound-measuring project, we felt that the most significant measure of annoyance was Kryter's Perceived Noise Level (PNdB). This scheme was developed to evaluate the annoyance caused by jet aircraft, and should give valid results for noises with similar frequency spectra (17, 18). The engine-driven tools used in our study have spectra roughly similar to those of commercial jets. Recent work by Botsford of the Bethlehem Steel Company has shown that the sophistication inherent in this method is not necessary (4). George and Eibner have presented similar conclusions (14). Botsford suggests that C- and A-weighted scales (see figure 2) adequately characterize the sound.

All of the methods presently used to estimate human response to noise, including PNdB, are based on both intensity and spectral content. Thus, a single number index of human response is valid over only a portion of the possible range of noise intensities and spectral contents. This shortcoming would exist for any single weighted level. But the C- and A-weighted levels combined indicate the type, or spectrum, of noise under consideration, and thereby permit the development of more precise relations.

Therefore, any new weighting network cannot be expected to lead to more precise relations than those derived using the C- and A-weighted sound levels. In many cases, the relations depend so slightly on the C-weighted sound level that it could be dispensed with and the A-weighted level alone used. In addition to greatly simplifying necessary data reduction calculations, the use of A-weighted levels as a standard method to determine human response to noises under sylvan conditions could enable Forest officers equipped with only meager acoustic knowledge and an inexpensive instrument to carry out noise surveys that have real meaning.

The correlation of any noise index with the human responses elicited in a wide group is inherently poor because of the wide variation of individual responses to the same stimulus. Better correlations can be obtained only by taking into account the social and psychological parameters responsible for these variations. Better correlations cannot be obtained by refining the noise measurement and evaluation procedure. This fact is illustrated clearly by the diagram in figure 8. The coefficient of correlation between any noise rating number and human response is represented by r_1, which is typically 0.85 or less. The coefficient of correlation found between sound levels, dBA, and noise rating numbers, PNdB, designated r_2, is typically 0.98 or better. The coefficient of correlation relating sound level directly to human response is r_3, which is equal to the product of the other two ($0.98 \times 0.85 \simeq 0.84$). Because r_2 is nearly unity, r_3 is essentially equal to r_1. Thus, sound levels correlate with human responses as well as any of the noise ratings. So refinement of noise

rating methods beyond sound levels is a futile exercise as far as the improvement of ability to appriase human response is concerned.

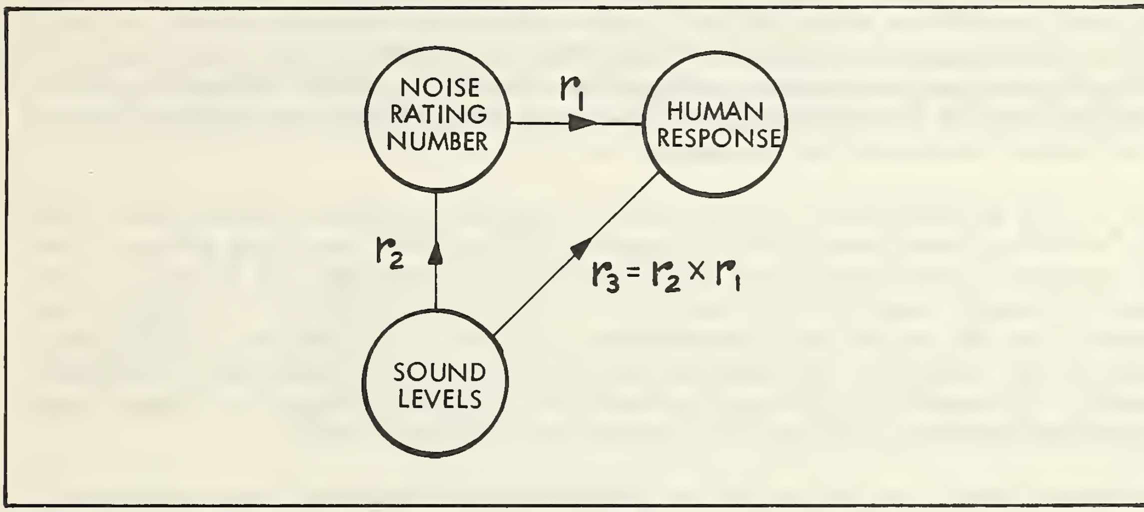
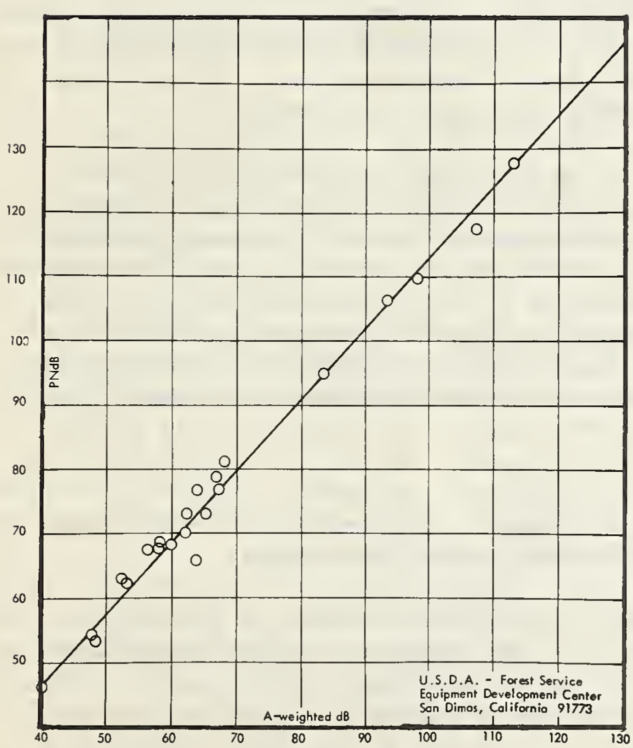


Figure 8. Intercorrelations among human responses, sound levels, and other noise ratings.



Data taken at site 2 were reduced to both A-weighted sound levels and perceived noise levels. The data and sum-of-the-least squares correlation curve are shown in figure 9. The equation for this straight line is:

$$\text{PNdB} = 1.098\ \text{dBA} + 2.400$$

Figure 9. Correlation: PNdB and dBA, site 2.

The correlation coefficient was found to be 0.989. Data from each of the other sites were spot-checked, and both PNdB and dBA were calculated for several of the noises. In each case the results pointed to a similar conclusion; that is, that a high degree of correlation exists between the A-weighted sound level and the perceived noise. This degree of correlation is higher than the correlation shown between subjective human response and any noise rating system. Therefore, it seems logical to conclude that the A-weighted sound level is an adequate descriptor of the noisiness of any sounds considered in this report.

One of the objectives of this study was to assess the annoyance caused forest users by the noises investigated, and to suggest a "noise limit" for forest areas. Since the amount of annoyance that a forest visitor experiences from the intrusion of any sound is largely based on the connotation of that sound, and not on its level, one approach to the reduction or elimination of acoustic annoyances in forest areas would be to insist that the sound be completely muffled or submerged in the background. This means that the sound pressure level caused by forestry equipment must be reduced to about 15 dB below the prevailing background noise.

Background levels as low as 38 dBA were measured during the course of this study, with the average being measured at 49 dBA. Thus, a "noise limit" criterion of about 20 to 25 dBA seems to be indicated. Note that it will be impossible to measure a noise of 25 dBA in a 40 dBA background. The level of the intruding sound will have to be calculated, or listened for by a group of observers.

Consider a noise source with a sound level of 100 dBA at 50 ft, such as a poorly muffled chain saw. This saw would have to be removed over a mile from the receiver to be completely inaudible under normal forest conditions. Unusual topography or atmospheric conditions could easily quadruple this distance.

In the opinion of some Forest officers, sounds of the type represented by the first 7 sound sources in our list of 11 sources are more acceptable under forest conditions than the last 4, because the first 7 do not intrude into the "wilderness experience" nearly as much as the last 4 (26). The personality of the receiver is one of the most important factors in determining how annoying a sound appears to be (20). The English Minister for Science has concluded that "the same noise may give rise to a greater annoyance in the country (than in the city) on account of the lower background; for the same reason a lesser noise may cause significant annoyance" (20). It is the sound's connotation that affects the users of the forest, not its level or duration (22).

Bearing this in mind, it is possible that some higher criterion be allowed for noises that do not hold unpleasant connotations for most users of forest areas.

Another possible basis for a noise criterion for wilderness areas, if one accepts a suggestion that complete loss of the sound in the background is too restrictive, is one related to a situation that is familiar and acceptable to many people. The continuous "rumble" of traffic noise at distances of greater than a mile or two from any reasonably busy road is about 45 dBA. This number is commonly accepted as a reasonable noise level for sleeping areas in the suburbs of cities (21). With this set as a criterion, surely a large percentage of the forest users would find intrusions of

this magnitude odious and would complain about them. Probably the most sensible course would be to select something between the 20 or so dBA required for complete "silence" and the 45 dBA mentioned as a maximum.

It is important to consider the characteristics of the users of the area under consideration. Probably a lower criterion should be selected for areas where recreation is the only concern and "wilderness values" are critically important, than for areas that mix such activities as vehicle camping and nature trails.

CONCLUSIONS

Consideration of all data collected in the course of our tests and investigation lead to the following conclusions:

1. For the investigated range of forest settings with trees, little excess attenuation is caused by the vegetation. Indeed, the maximum total excess attenuation appears to be less than 10 dB at any of the sites where we conducted tests.

2. Any excess attenuation that is caused by forest trees and ground cover is greatly dependent on terrain type, and is difficult to assess.

3. For the brush and meadow conditions investigated, the excess attenuation is insignificant, averaging about 1 dB per 100 ft, up to a maximum of about 10 dB at frequencies of less than 1 KHz, and is 15 dB at higher frequencies.

4. It is best to use spherical divergence to estimate the distance needed between a receiver and a noise source to achieve desired levels of quiet in the forest. (Recognize, though, that this will slightly over-estimate the distance.)

5. Subjective considerations make the quantification of annoyance under forest conditions difficult. However, A-weighted levels are as valid and as simple a measure of noise annoyance as has yet been devised.

6. The criterion for allowable noise intrusion for forested areas will depend upon the expectation of the particular forest user, but should probably be set at somewhere between 20 and 45 dBA.

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APPENDIX I

TEST INSTRUMENTATION, PROCEDURES, AND DATA REDUCTION

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Instrumentation

Two sets of instruments were used—that taken out to the field to permanently record noise signals on magnetic tape, and that in the laboratory at the Equipment Development Center to reduce the field data to usable numbers. The total instrumentation system is represented schematically in figure A1.

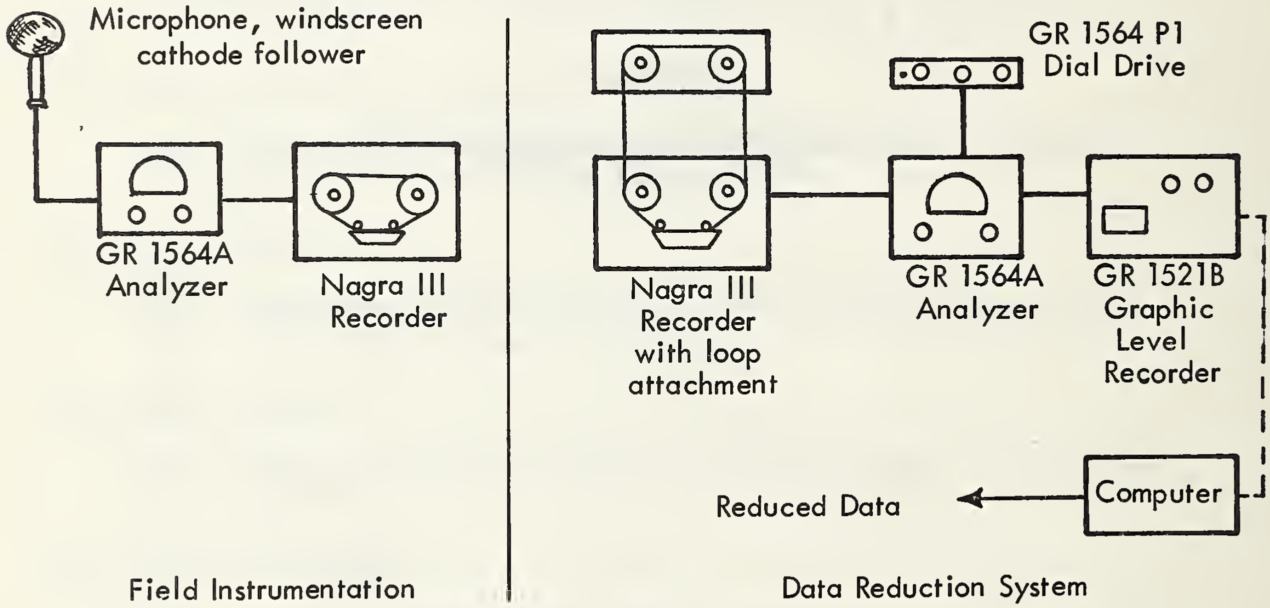


Figure A1. Instrumentation system.

There were three major elements in the system used for gathering data in the field (see figure A1). The microphone converted airborne acoustic signals to electrical signals. Because of the low levels encountered, a microphone alone was not sufficient but had to be coupled to a pre-amplifier (cathode follower). A Bruel & Kjaer 4131 microphone and a Bruel & Kjaer 2630 cathode follower were employed. A Bruel and Kjaer UA0082 windscreen was used to limit wind noise (7, 24).

The next element in the field instrumentation system was a General Radio 1564A sound and vibration analyzer (13). This had an amplifier that boosted the cathode follower output to a level that could be satisfactorily recorded on magnetic tape. The band width switch was set to "all pass". The amplifier in the analyzer had the important advantage of being attenuated in 10-dB steps. This calibration eliminated any input/output error caused by maladjustment of the amplifier.

The final element in the field instrumentation setup was an electronic tape recorder. A Kudelski Nagra III was used because its frequency response is flat within 1 dB throughout the entire audio range!

When the acoustic data recorded on the magnetic tape were returned to the laboratory, data reduction was accomplished using a four-element setup (see figure A1). The first link in the system was the tape recorder, used to play back the field data. Each datum was spliced into a 2-second loop, thus allowing a sound to be repeated continually for complete analysis. From the tape recorder the signal was fed into a General Radio 1564A sound and vibration analyzer. This time the filter band width was set on 1/3 octave. As the filter was stepped through 1/3 octave band center frequencies, all of the signal but that contained in the 1/3 octave band was filtered out. The remaining signal corresponded with the sound pressure level in that frequency band.

This 1/3 octave band signal was then fed into a General Radio 1521B graphic level recorder, which is a potentiometric strip-chart recorder. The 1564A analyzer and the graphic level recorder were coordinated automatically by a General Radio 1564-P1 dial drive. This device makes data analysis completely automatic, greatly reducing the possibility of human error. The 1/3 octave band sound pressure levels were thus permanently recorded and available for digitization and insertion into the computer for data processing.

Each data tape loop was reduced to 1/3 octave band pressure levels. The 1/3 octave band pressure levels were then summed and the result compared with the measured "all pass," or total signal. If the comparison was not within 3 dB, the datum was rejected.

Although this instrumentation system was calibrated before each run, and demonstrated a run-to-run repeatability of less than ±1 dB, the consistency of the data is not as good as had been hoped for. This is no fault of the instrumentation system, but rather of experimental techniques. As detailed bwloe in "Field Test Procedures," the level of each noise source was measured at each of several locations. Each of these measurements was separated rather widely in time; thus, atmospheric parameters could vary significantly. Also, it was impossible to insure consistency for some of the sources used, such as the motorcycle and power saw. A better method would have been to use several separate transducers and recorders placed at varying distances from the noise source. Then measurements could have been made simultaneously and atmospheric and source variables would have been eliminated.

Two other elements were utilized in the total instrumentation system. The first of these was a calibrator, B&K type 4220. This is a positive displacement device that produces 124-dB signal at the microphone at a frequency of 250 Hz. This signal was the standard against which all sound pressure levels were compared. The other element employed was an impact noise analyzer, General Radio 1556B. This analyzer allowed the data reduction technician to "see" transient noises (such as gunshots, pick and shovel work, etc.) whose rise time and decay were too rapid for the meter of the General Radio 1564A sound and vibration analyzer to track.

Field Test Procedures

A typical data-gathering day involved early arrival at the test site. The instrumentation was then set up, calibrated and checked. Figure A2 shows the microphone with windscreen fitted, amplifier, and recorder.

Figure A2. Field instrumentation.

Atmospheric conditions, such as wind, relative humidity, barometric pressure, and temperature were measured. When this preliminary work was completed, the measuring crew set out to the measuring site to place the receiver. The distance from the receiver to the source of the noise-making site varied between 100 and 1,500 ft.

Figure A3. Gathering field data.

Once the site was reached, the instruments were again calibrated and two-way radios were utilized to signal the "source" crew to commence making sounds. From three to seven separate locations were used for each source. Because of the low noise levels involved and the sensitivity of the instruments, it was necessary for the measuring crew to insure that their contribution to the background noise was not significant.

Figure A3 shows a typical receiver site during the process of recording data.

Data Reduction

After each noise was reduced to its 1/3 octave spectra, the following reduction procedure was utilized. (The reason for presenting the data reduction routine here is not to suggest it as a standard method, but merely to illustrate the data handling procedure used in the development of this report.) Figure A4 shows the data reduction instrumentation that was utilized.

Figure A4. Data reduction instrumentation in use.

The data reduction routine consisted of four steps:

1. The 1/3 octave band sound pressure levels for each loop were summed and compared with the measured all-pass. This was a check to determine that the 1/3 octave analysis was done accurately. When the sum of the 1/3 octave band sound pressure levels was within 3 dB of the field measured all-pass, it was assumed that a valid 1/3 octave analysis had been made.

2. Instrument and background corrections were applied to the data as necessary. One correction compensated for frequency non-linearities in the recorder, microphone, amplifier, and play-back systems. This correction was quite small (at most

frequencies, zero). Another correction adjusted the calibrator level as a function of barometric pressure. Although pressure had little effect on the actual acoustic data, it did significantly affect the calibrate level produced by the pistonphone.

It was originally planned not to use any measurements in which the noise under study was less than 7 dB greater than the background noise. However, this proved to be impractical, so noises as little as 4 dB above the background were used. In this case a small correction had to be made (see figure A5).

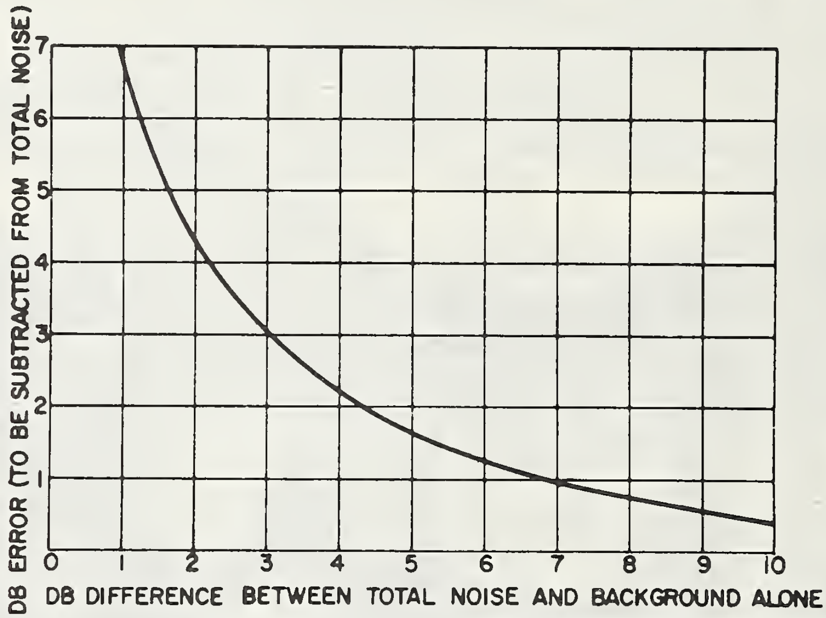


Figure A5. Effect of background noise on sound data.

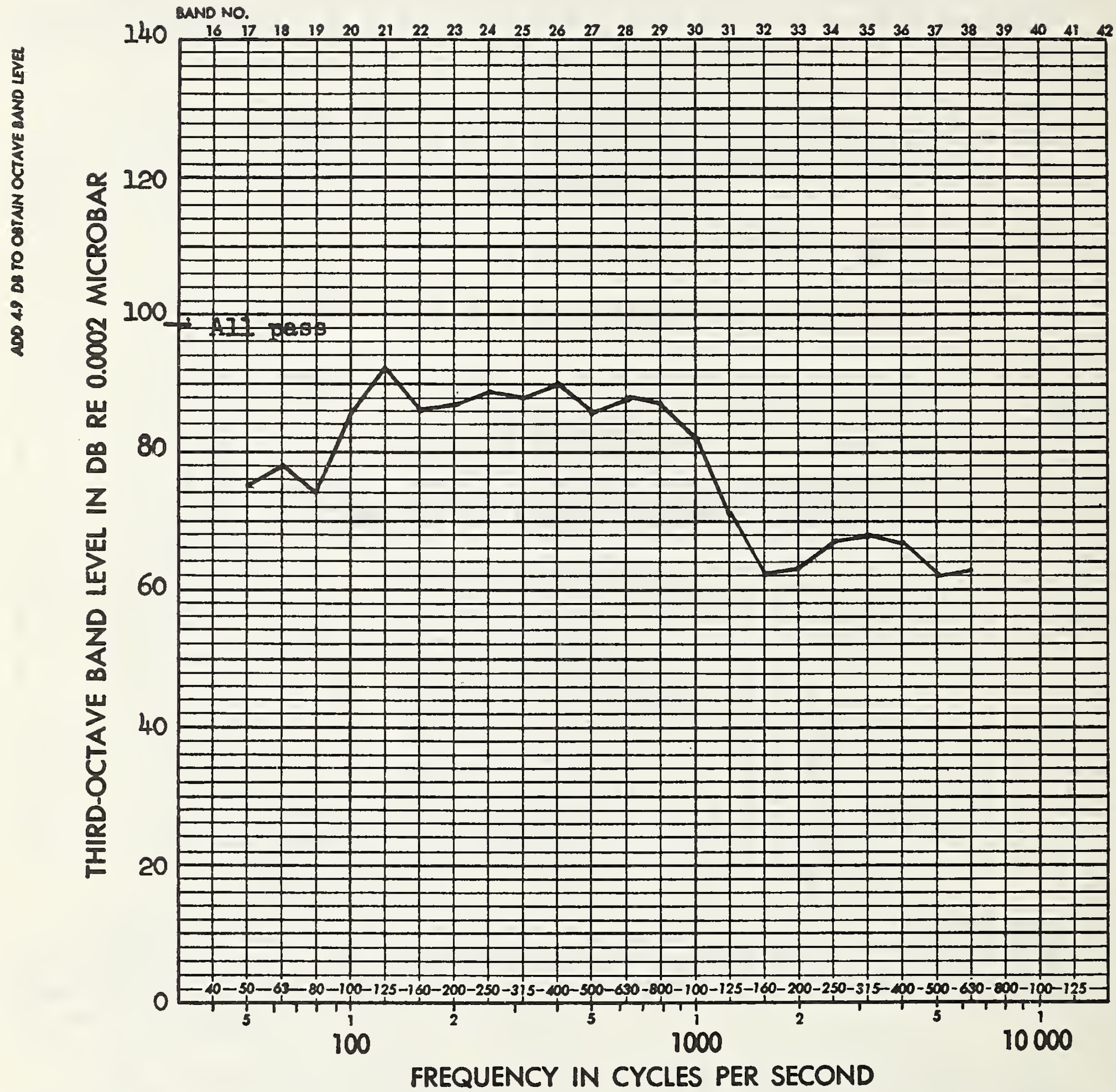
3. Sound levels, dBA, were calculated from the "corrected" 1/3 octave band sound pressure levels. This operation involved applying the weighting shown in figure 2 to each of the 1/3 octave band sound pressure levels and summing them logarithmically to obtain a sound level figure.

4. The last step was to determine excess attenuation, which was done by calculating the level that would be expected at a given distance (see the equation under the subsection "Effect of Distance"), and subtracting from this figure the measured sound pressure level at the same point. The difference was normalized to dB per 100 ft, the unit of excess attenuation. Note that the excess attenuation considers all factors of the forest environment, including modifications to the microclimate and the effect of ground cover, as well as the effect of trees and brush. In the calculation of excess attenuation only data taken at distances of up to about 500 ft were used, because of the propagation of sound over the top of the trees and brush.

The data reduction was done almost entirely on a Hewlett-Packard 9100B programmable calculator, although some of the more easily programmed reduction steps were handled on a large computer at a local university.

APPENDIX II

REPRESENTATIVE 1/3 OCTAVE SPECTRA FOR SOURCE-RECEIVER DISTANCE OF 100 FT



WELDER

U.S.D.A. FOREST SERVICE
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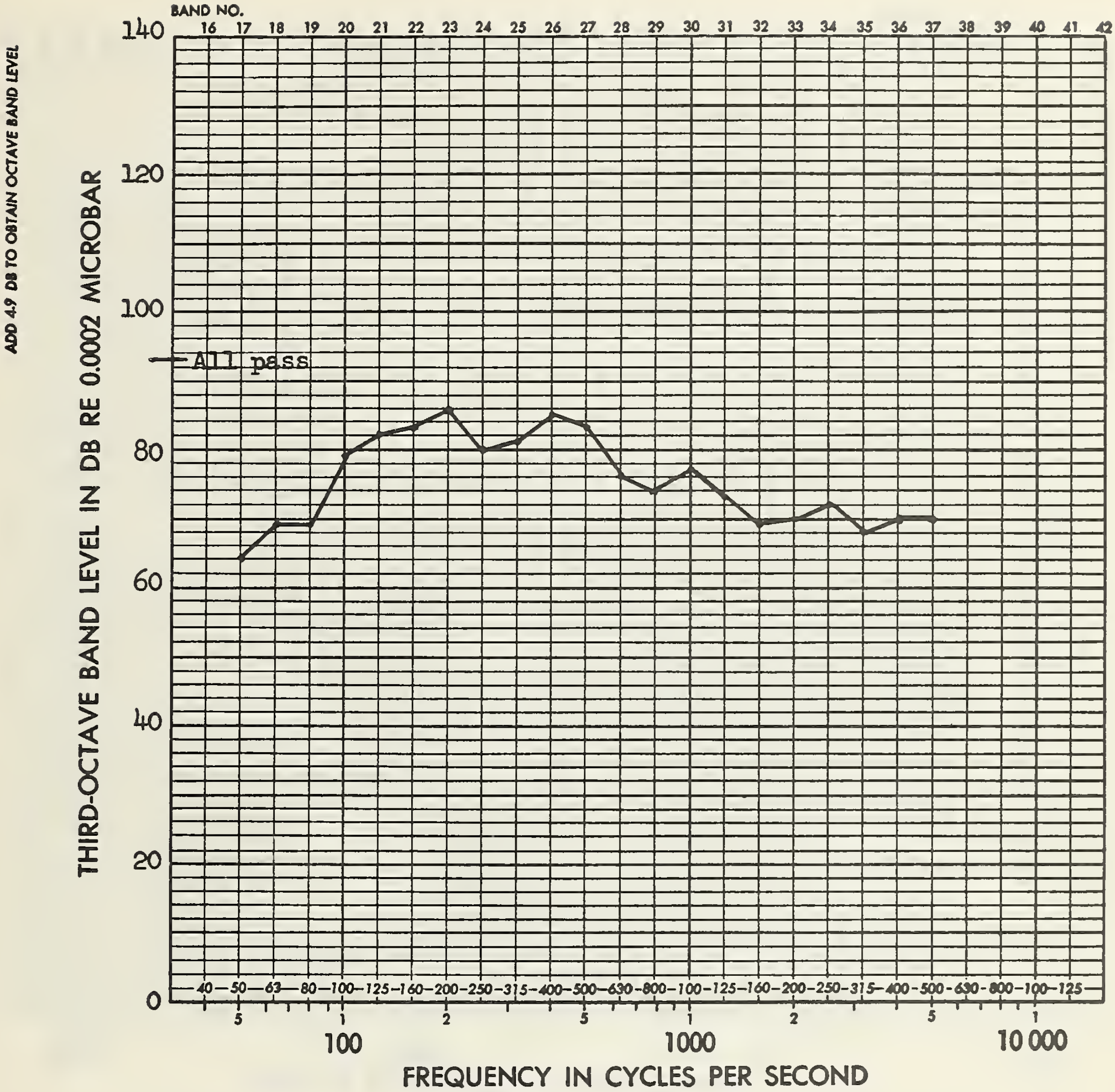

CHAIN SAW

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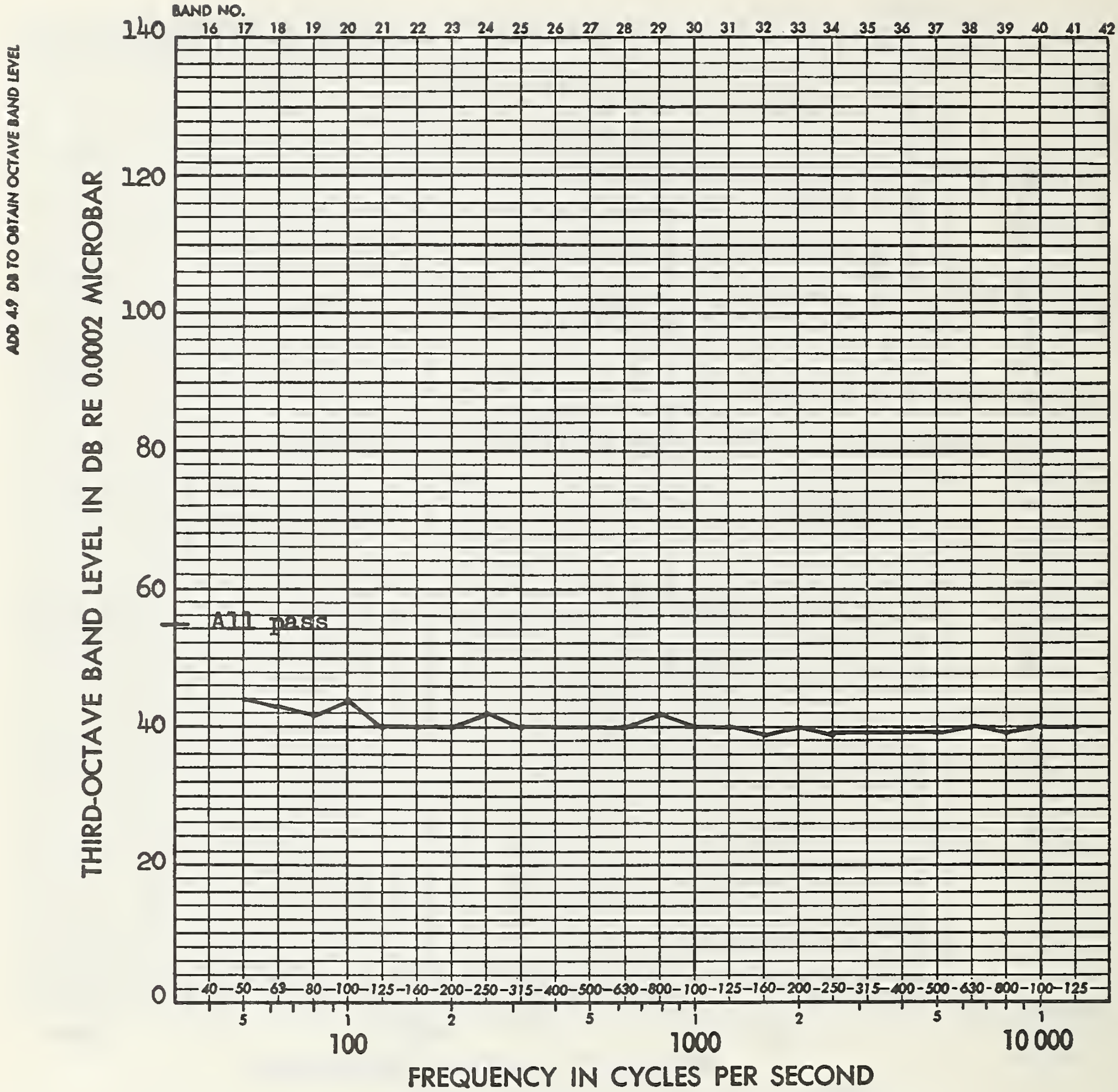

2-MAN SAW

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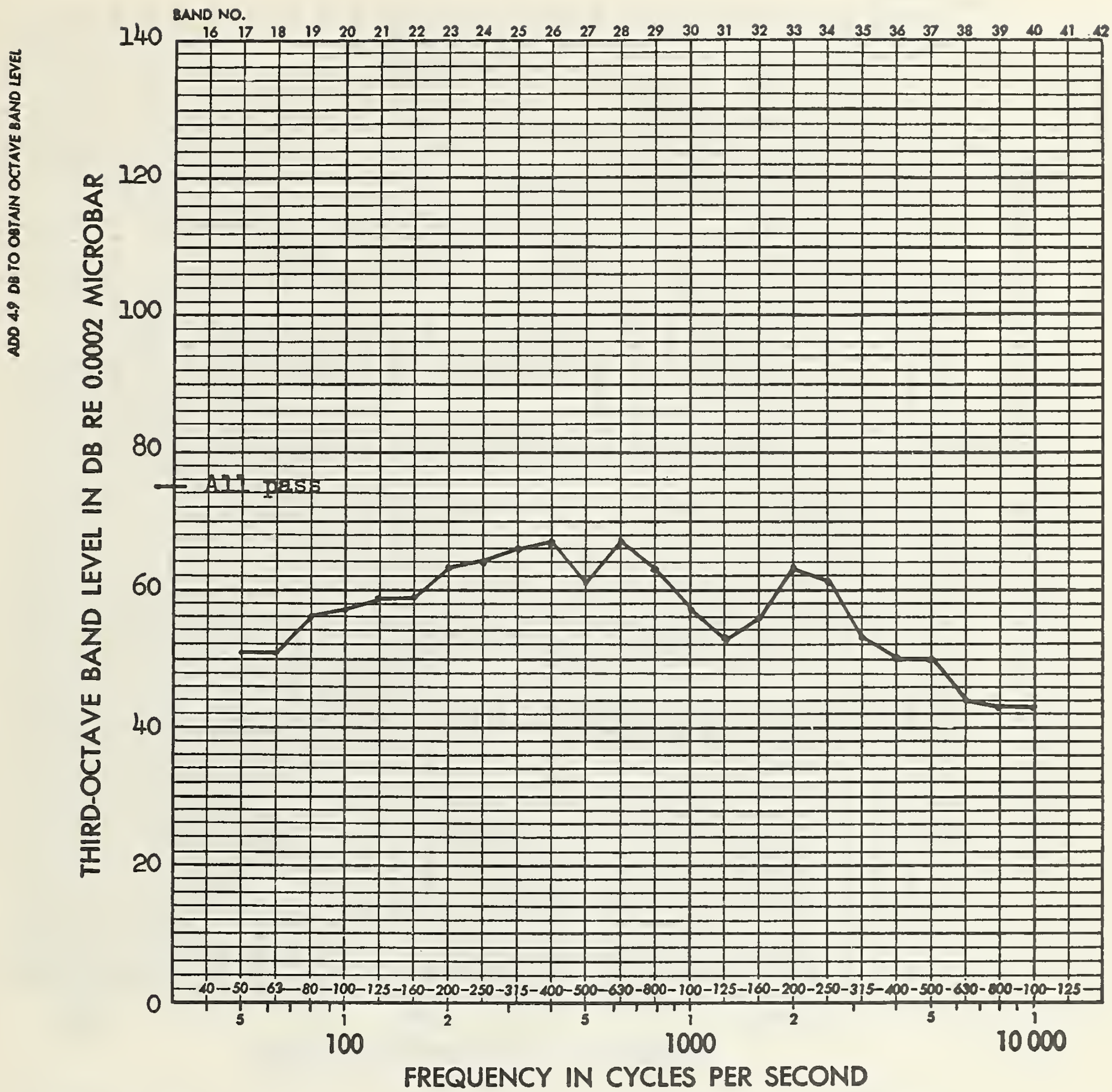

AXE

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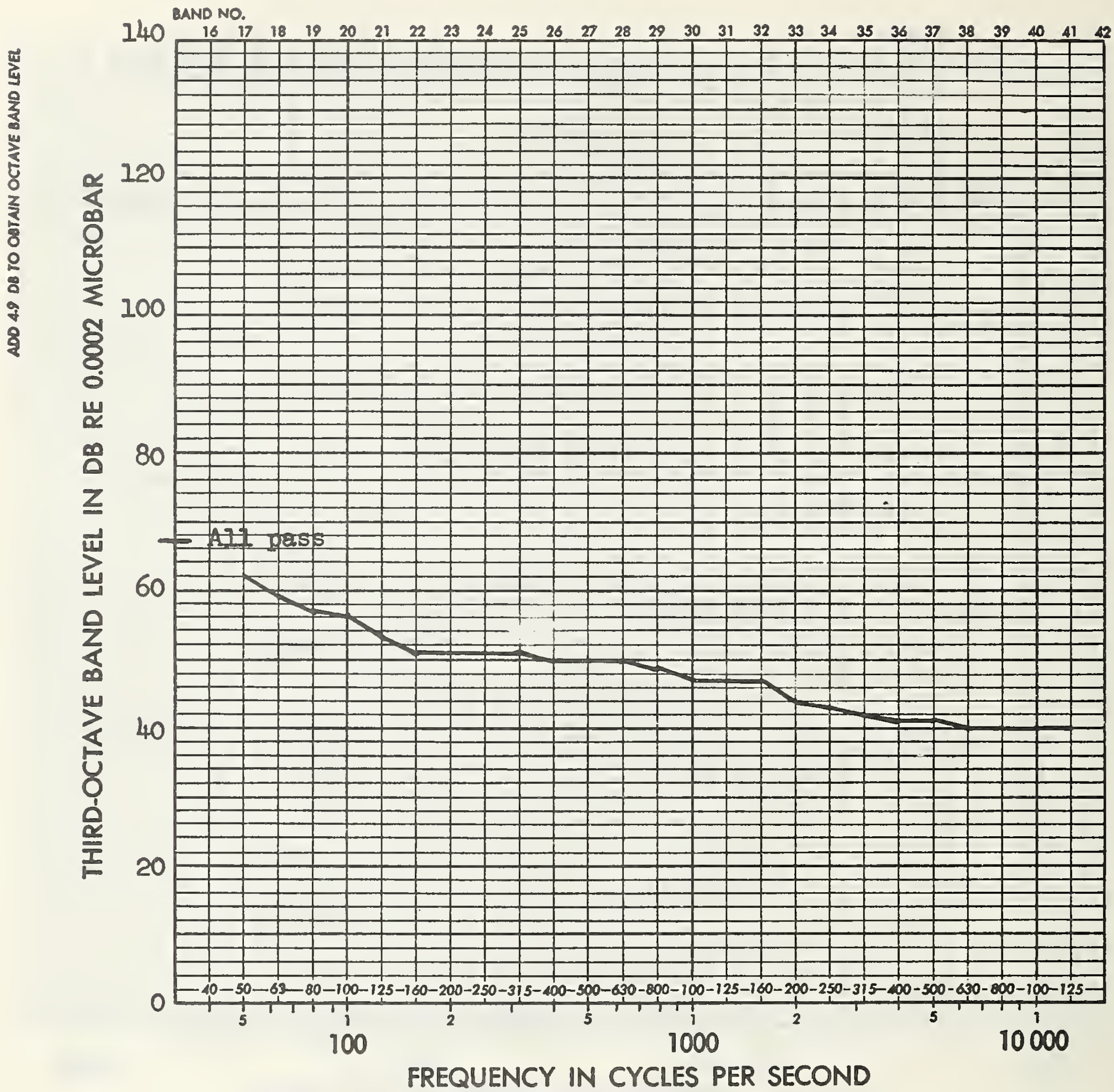

SHOUTING

U.S.D.A. FOREST SERVICE
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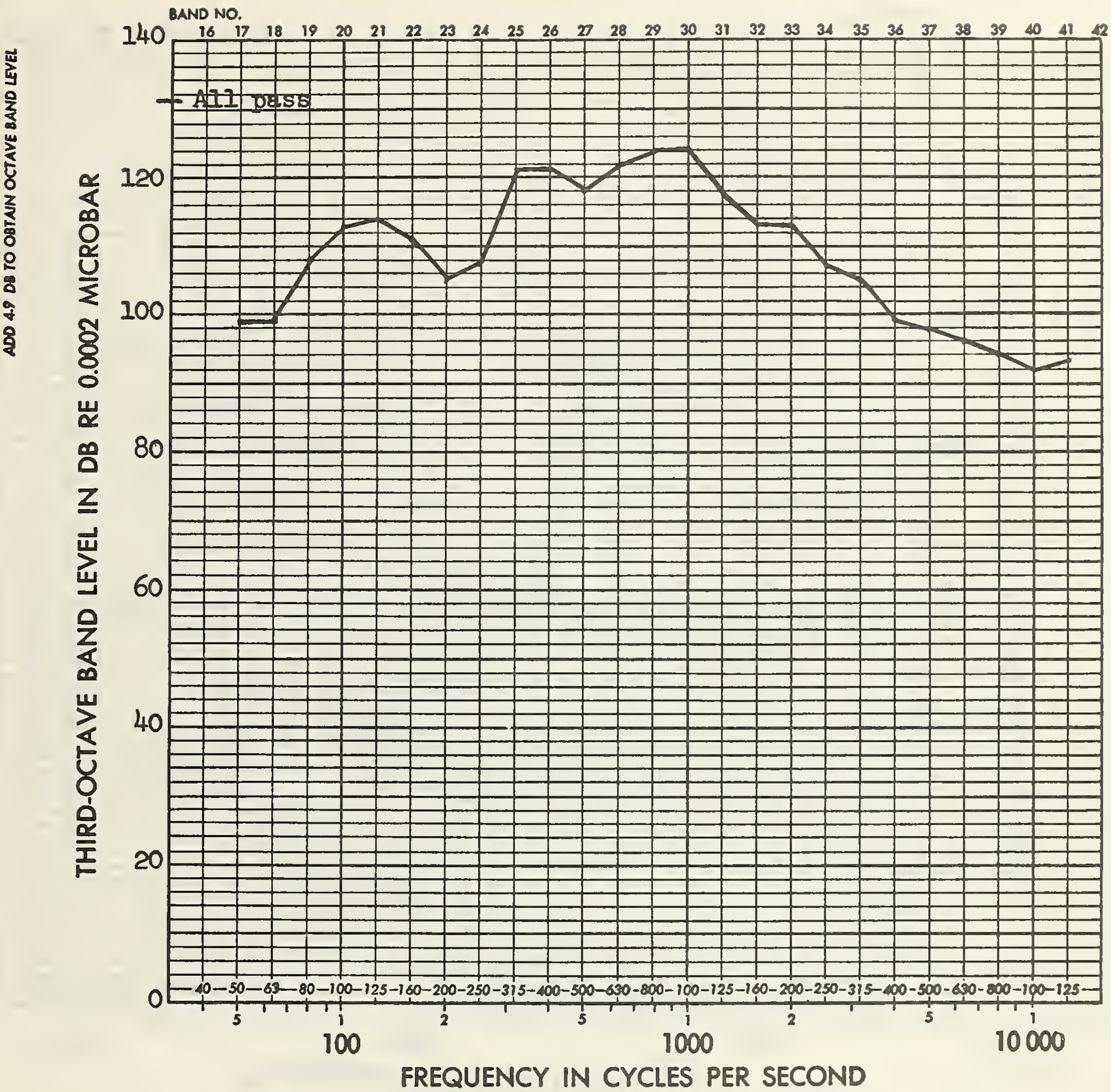

RIFLE

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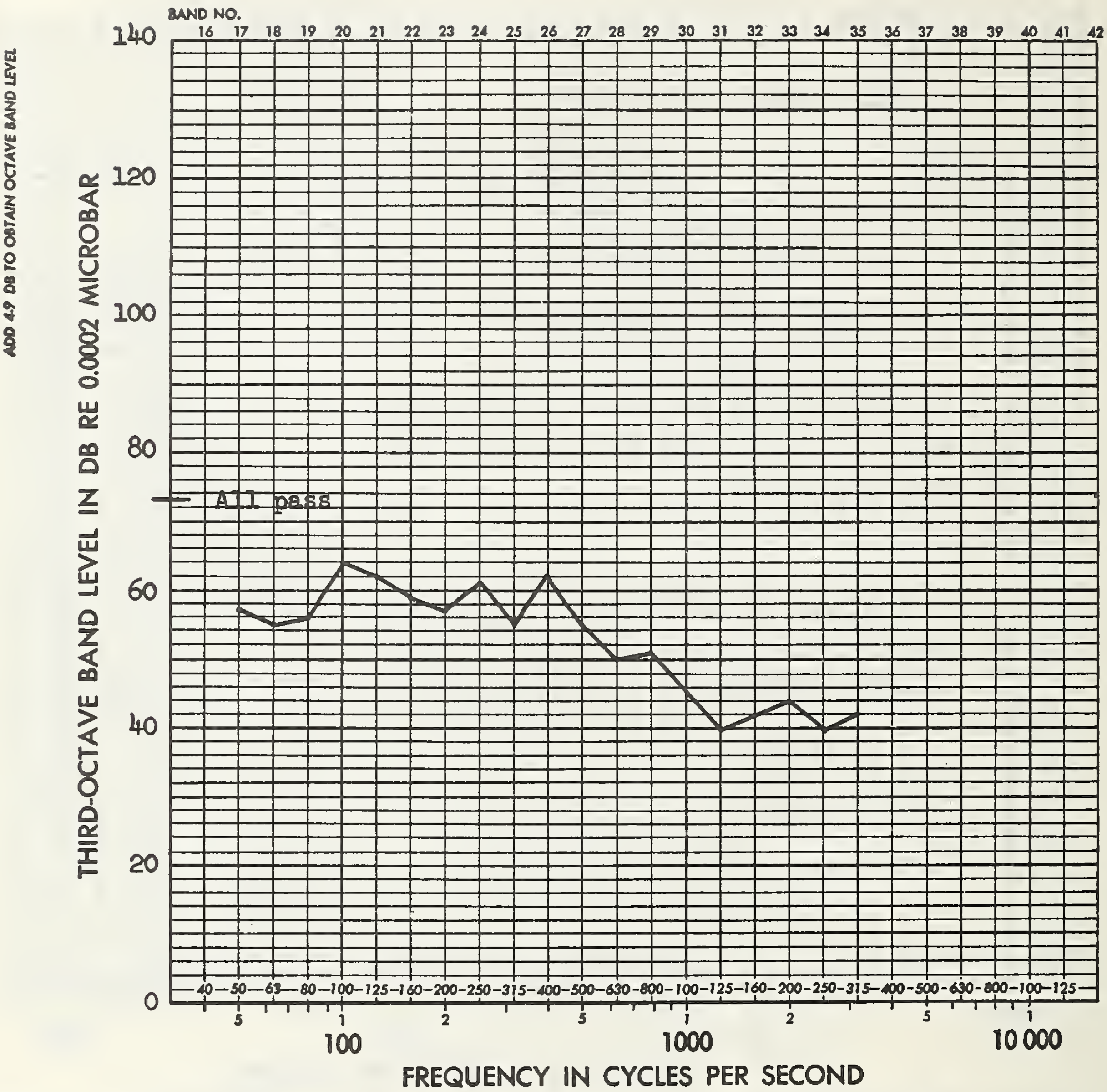

TRUCK

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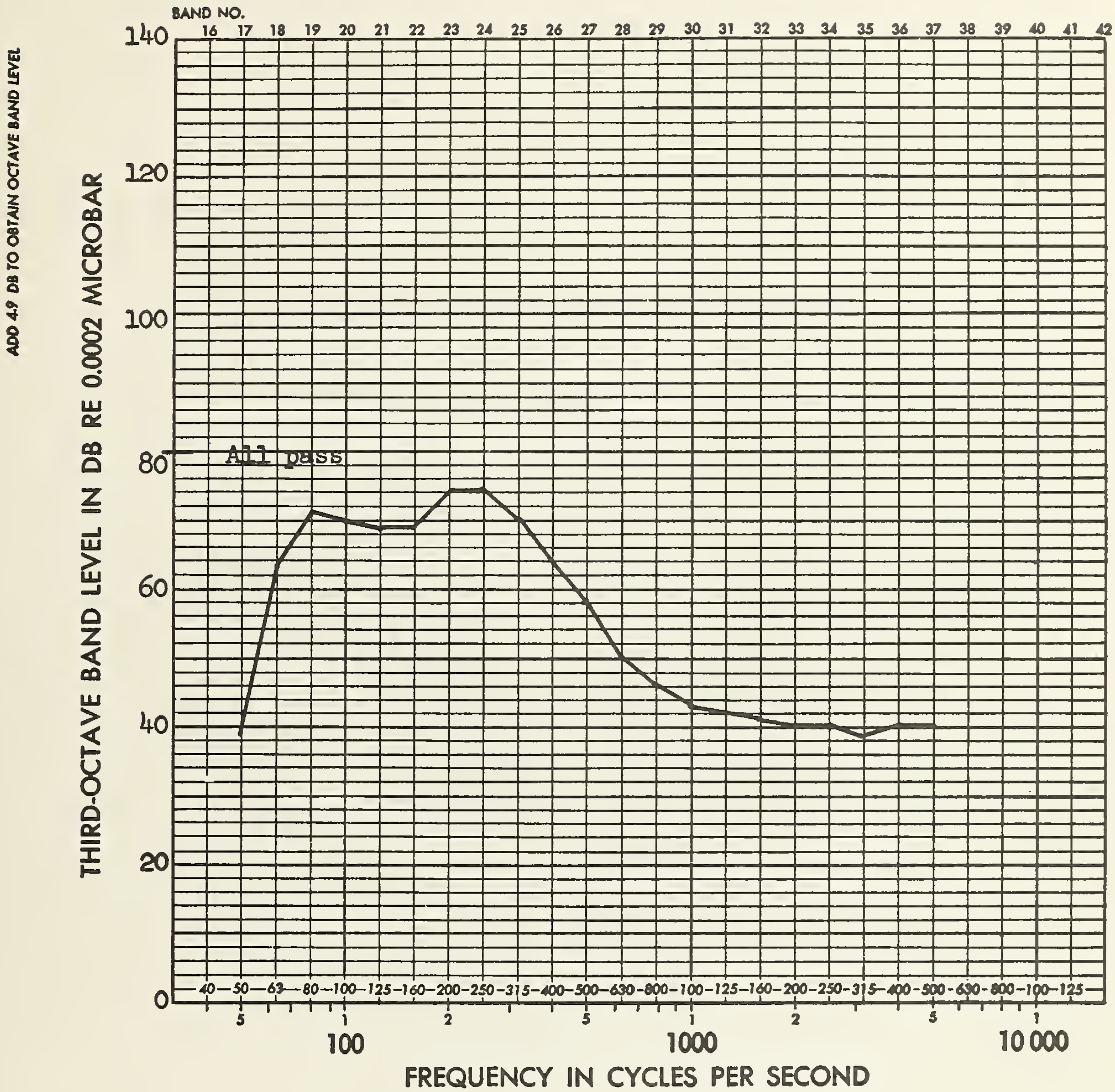

TRAIL SCOOTER

U.S.D.A. FOREST SERVICE
SAN DIMAS EDC 7-10-70

GPO 874-931